NASA Electronic Parts and Packaging (NEPP) Program

Leakage Currents in Low-Voltage PME and BME Ceramic Capacitors

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List of Acronyms and Symbols

BME	base metal electrode capacitor	μ	mobility of electrons
J	current density	MLCC	multilayer ceramic capacitor
β_s	Schottky constant	n_V	voltage acceleration constant
χ	quasi static electric susceptibility	PME	precious metal electrode capacitor
C_0	nominal capacitance	Q_t	absorption charge
C_t	absorption capacitance	RT	room temperature
d	thickness of the dielectric	σ	surface charge density
DCL	direct current leakage	S	surface area
E	Electric field	SCLC	space charge leakage current
ε	dielectric constant	t_{el}	electrification time
Φ_B	barrier heights	TTF	time to failure
HALT	highly accelerated life testing	U	activation energy of leakage currents
HT	high temperature	VBR	breakdown voltage
I_{abs}	absorption current	VBR_d	breakdown voltage due to defects
IM	infant mortality	VBR_i	intrinsic breakdown voltage
IR	insulation resistance	V_O^{++}	charged oxygen vacancy
k	Boltzmann constant	VR	rated voltage

Abstract

Introduction of BME capacitors to high-reliability electronics as a replacement for PME capacitors requires better understanding of changes in performance and reliability of MLCCs to set justified screening and qualification requirements. In this work, absorption and leakage currents in various lots of commercial and military grade X7R MLCCs rated to 100V and less have been measured to reveal difference in behavior of PME and BME capacitors in a wide range of voltages and temperatures. Degradation of leakage currents and failures in virgin capacitors and capacitors with introduced cracks has been studied at different voltages and temperatures during step stress highly accelerated life testing. Mechanisms of charge absorption, conduction and degradation have been discussed and a failure model in capacitors with defects suggested.

Outline

- Introduction.
- Leakage currents.
  - Absorption currents and room temperature IR.
  - Intrinsic leakage currents and high temperature IR.
- Degradation of leakage currents during HALT.
- Effect of cracking on degradation of leakage currents at high temperatures.
- Models of degradation and failures for BME capacitors with defects.
- Conclusion.

Introduction

- Stability of DCL or IR at environmental testing indicates reliability of MLCCs.
- Currently, hi-rel systems employ MLCCs with Ag/Pd metal electrodes.
- Insertion of BME capacitors in hi-rel applications requires a closer look at differences in DCL for PMEs and BMEs under environmental stresses.
- Reliability issues with MLCC:
  - Degradation of IR related to oxygen vacancies.
  - Failures related to manufacturing defects.
  - Failures related to soldering and assembly introduced cracking.
  - Effect of moisture and low-voltage phenomena.
- Intrinsic wear-out failures caused by oxygen vacancies typically do not cause failures during applications. Reliability is limited by defects.
- A limited data exist on the effect of cracking on degradation of leakage currents.

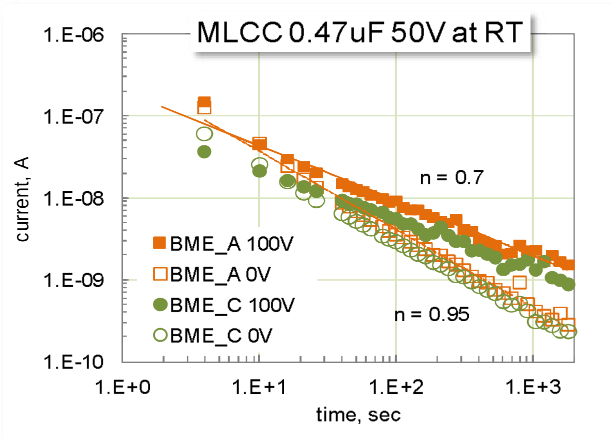
Part Types Used in This Study

C, μF	VR, V	Part type	Mfr.	application	EIA size	d, μm	C, μF	VR, V	Part type	Mfr.	application	EIA size	d, μm
0.33	50	**PME**	V	MIL	1825	25	1	50	BME	A	Gen.	1825	25
0.33	50	**PME**	C	MIL	1825	30	1	100	**PME**	P	Hi-rel	2225	25
0.33	50	BME	C	Gen.	1210	12	2.2	50	BME	C	auto	1206	6
0.33	50	BME	A	Gen.	1210	16	2.2	50	BME	C	auto	1210	6
0.33	50	BME	A	auto	0805	9	2.2	50	BME	A	auto	1210	10
0.33	50	BME	A	Gen.	0805	9	2.2	100	BME	A	auto	1812	12
0.33	50	BME	M	auto	0805	7	2.2	50	**PME**	A	MIL	stack	31
0.33	50	BME	M	Gen.	0805	7	0.1	50	BME	C	Gen.	1210	13
0.33	50	BME	C	auto	0805	6	0.1	50	BME	A	Gen.	1210	24
0.33	50	BME	C	Gen.	0805	6	0.1	50	**PME**	C	MIL	1210	24
1	10	BME	A	Gen.	0805	5.1	0.1	50	**PME**	A	MIL	1210	26
1	10	BME	C	auto	0805	3.5	0.47	50	**PME**	V	MIL	1825	22
1	10	BME	M	Gen.	0805	4.2	0.47	50	**PME**	C	MIL	1825	21
1	10	**PME**	P	Hi-rel	0805	10	0.47	50	BME	C	Gen.	1825	24
							0.47	50	BME	A	Gen.	1825	28

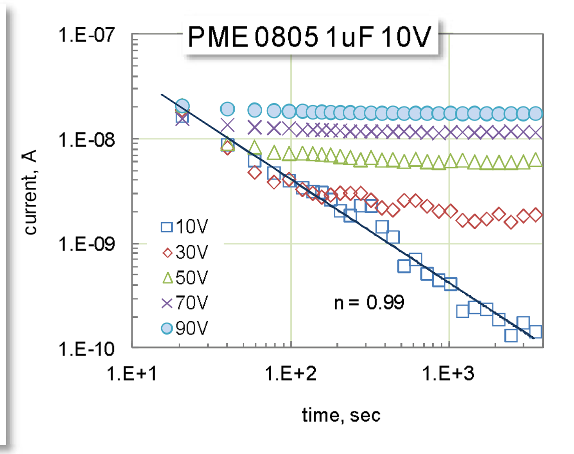
✓Six groups of similar PME and BME X7R capacitors from 5 mfrs.
✓Cracks were introduced using Vickers indenter.

Absorption and Intrinsic Leakage Currents

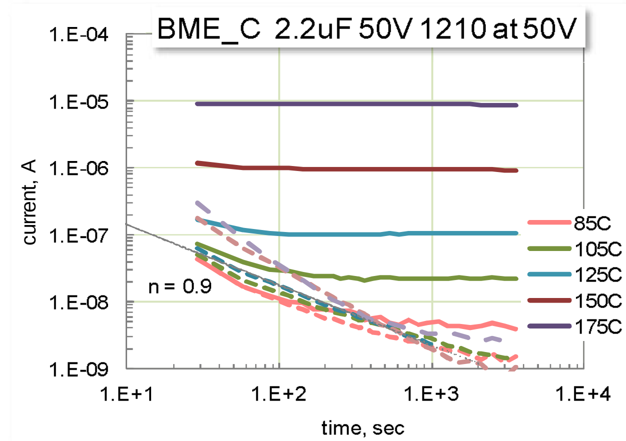
Polarization and depolarization currents



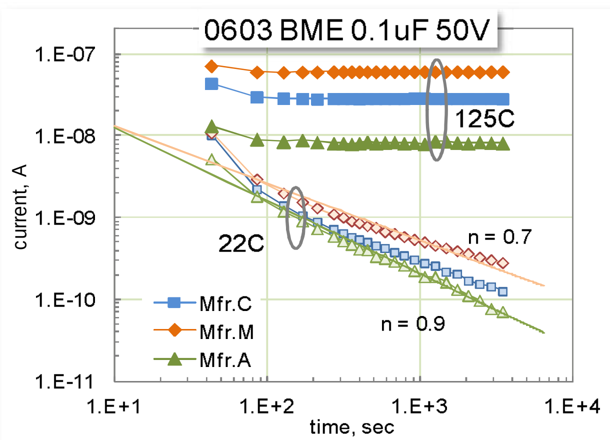
Effect of voltage at room temperature



Effect of temperature at rated voltage



MLCCs from different vendors

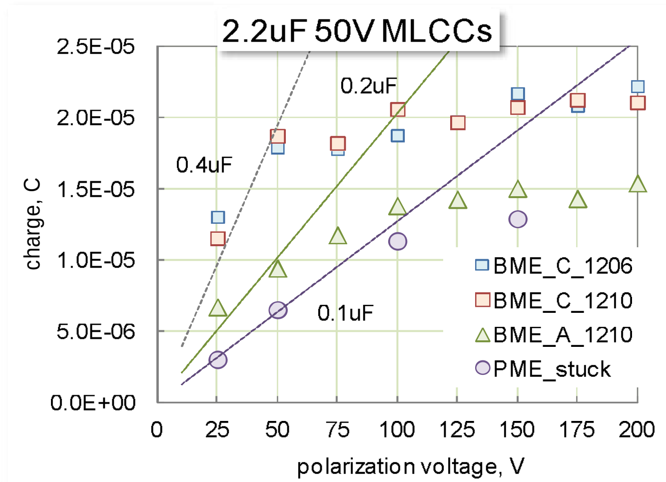


- ✓ Absorption currents in both, PMEs and BMEs, follow Curie–von Schweidler law ($I \sim t^{-n}$), prevail at VR and RT, have a poor temperature dependence, and vary mostly with the value of capacitance.
- ✓ Intrinsic leakage currents prevail at high temperatures and/or V >> VR.

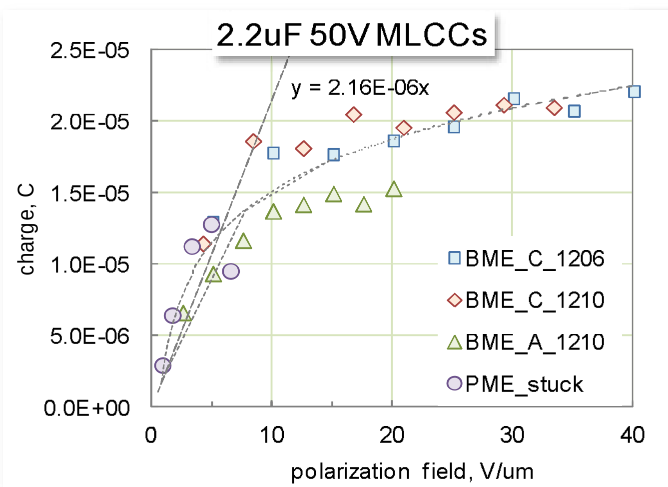
Absorption Charge

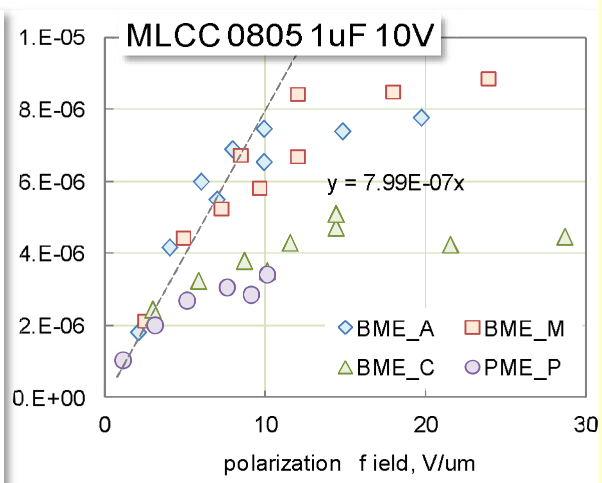
- ❑ Absorption charge:

$$Q_t = \int_1^{1000} I_0 \times t^{-n} \times dt = \frac{I_0}{1-n} \times t^{1-n} \Big|_1^{1000}$$



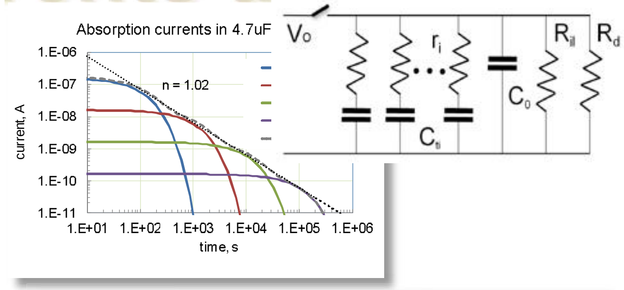
- ❑ $Q_t \sim V$ at V < (2-3)VR => validation of IR.
- ❑ $Q_t = \varepsilon_0 \times \chi \times S \times E$
- ❑ Absorption capacitance: $C_t = Q_t/V$.





✓C_t for BMEs is in the range from $0.05 \times C_0$ to $0.2 \times C_0$.
✓C_t for PMEs is ~2 times less than for BMEs.
✓Polarization saturates at E> 5V/um

Modeling of Absorption Currents and IR



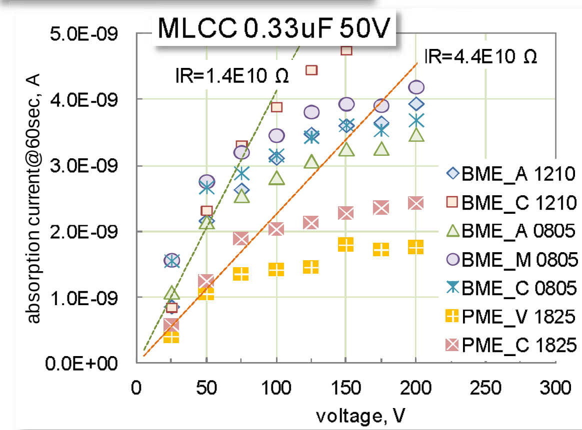
- Dow model for a capacitor with absorption:

$$I(t,V) = \frac{V_0}{R_d} + \frac{V_0}{R_{il}} + \sum_i \frac{V_0}{r_i} \exp\left(-t/\tau_i\right)$$

- IR ≈ r_i measured at t_{el} => $IR \approx t_{el}/C_{ti}$.

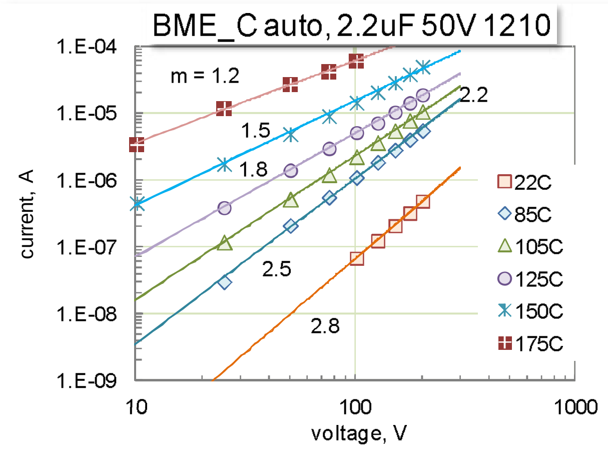
$$C_t = \frac{Q_t}{V} = \frac{\sigma \times S}{V} = \frac{\varepsilon_0 \times \chi \times S}{d} = \frac{\chi \times C_0}{\varepsilon} \Rightarrow \boxed{IR \approx \frac{t_{el} \times \varepsilon}{\chi \times C_0}}$$

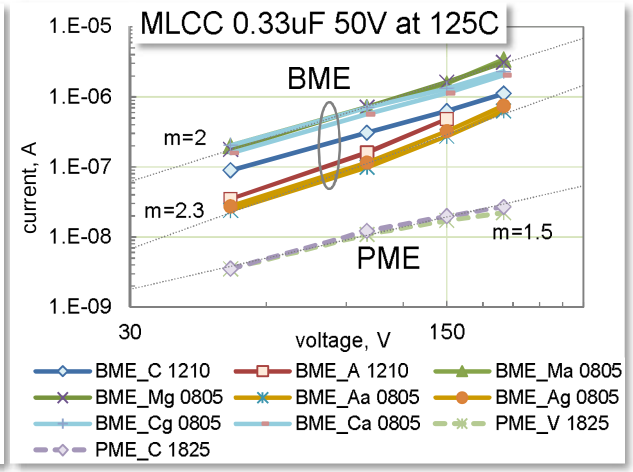
- At t_{el} ~ 100 sec and ε/χ ~ 5 to 20, $IR \sim 10^9/C_0$ (IR in Ω, C_o is in μF), which is close to experimental values.

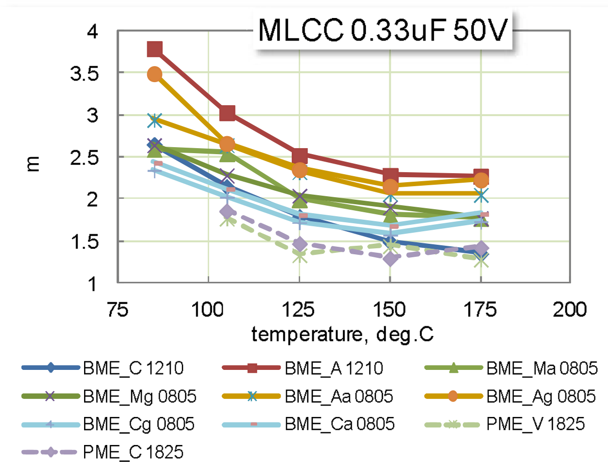


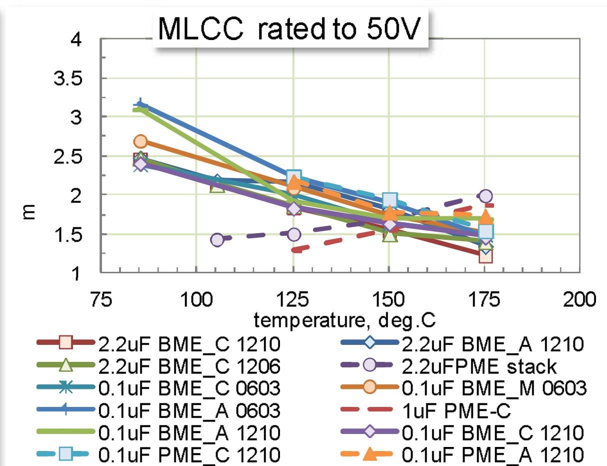
- ✓ Relaxation of I_{abs} in a wide range of times can be presented as a superposition of currents through a few r_i - C_{ti} relaxators.
- ✓ The model explains IR dependence on capacitance and is in a reasonable agreement with the measured IR values at RT.
- ✓ $I_{abs\ BME}$ is ~ 2 times larger than $I_{abs\ PME}$ => different requirements.
- ✓ At RT DCL and IR are determined by electron trapping (N_t ~ 2-6×10^{13} cm^{-2}) at the GBs or electrode/ceramic interface(?).

Voltage Dependence of Intrinsic DCL









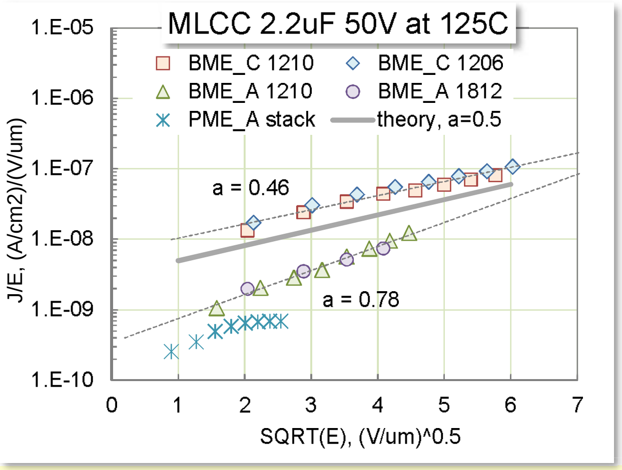
- ✓ *I-V* characteristics of PME and BME capacitors at HT can be described with a power function, $I \sim V^m$.
- ✓ The exponent *m* decreases with temperature from 2.5 to 4 at 85°C to 1.2 < *m* < 2.5 at 175°C.
- ✓ Mechanism of conduction (SCLC?)

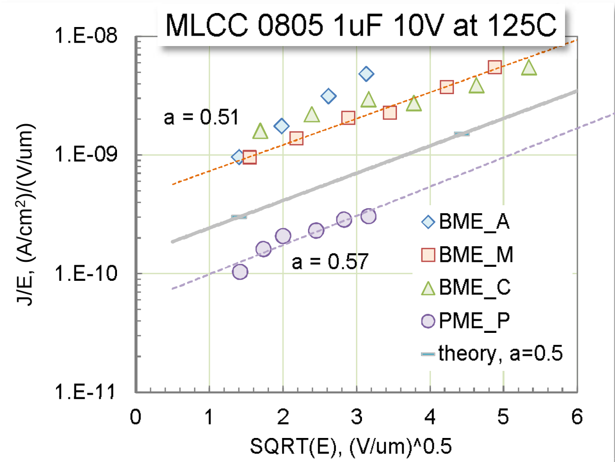
Field Dependence of Intrinsic DCL

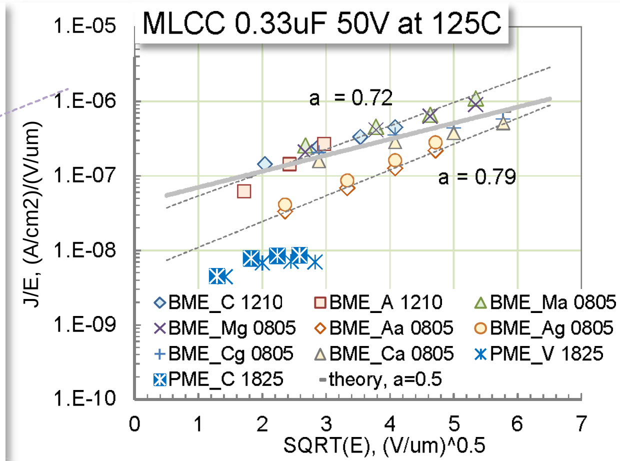
- Simmons model (injection is interface controlled, and the transport is bulk-limited)

$$J_s \sim \mu E \exp\left(-\frac{q\Phi_B - \beta_s E^{1/2}}{kT}\right)$$

- At 125°C the slope of *J/E vs $E^{0.5}$* curves, $\beta_s/kT = \alpha \approx 0.5\ (\mu m/V)^{0.5}$







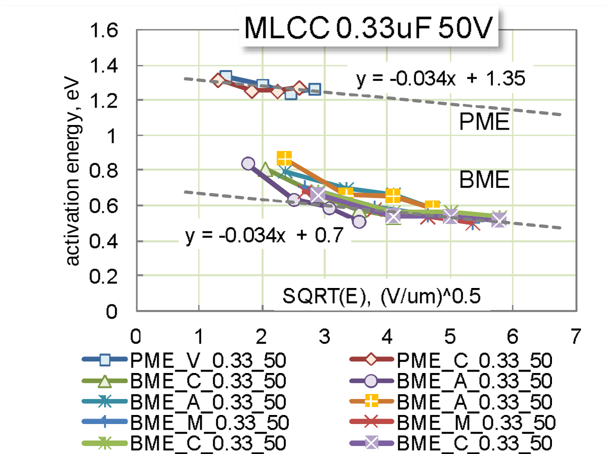
- ✓ Leakage currents at 125°C are in a reasonable agreement with the Simmons model.
- ✓ Degradation due to V_O^{++} can be modeled by variations of Φ_B with time.
- ✓ At similar electric fields, conduction , *J/E,* in BMEs is several times greater than in PMEs.
- ✓ Is the difference of conductivity for different BMEs due to different μ?

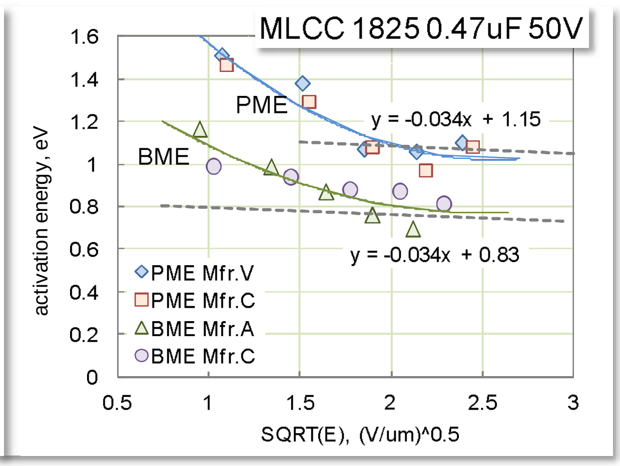
Activation Energy of Intrinsic Currents

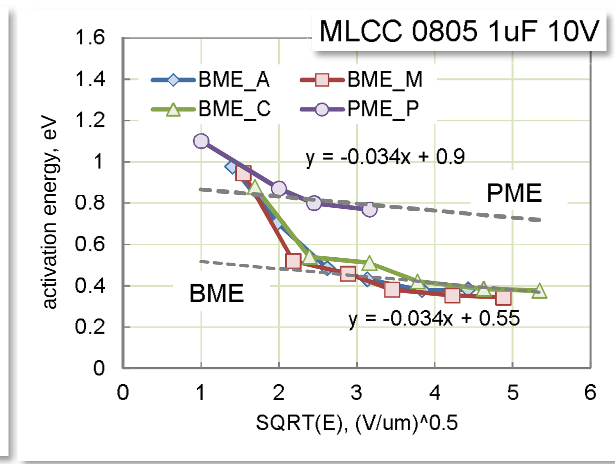
- Simmons model: $U = \Phi_B - \beta'_s E^{1/2}$, β'_s= 0.034 eV*(μm/V)$^{0.5}$
- No changes in activation energy through Curie temperature (125 ºC).
- A decrease of *U* with *E* follows Simmons model at *E* > 5 V/μm.

Activation energies for PMEs and BMEs at VR

	PME	BME
U_{avr}, eV	1.19	0.83
STD, eV	0.14	0.13
Part types	10	23







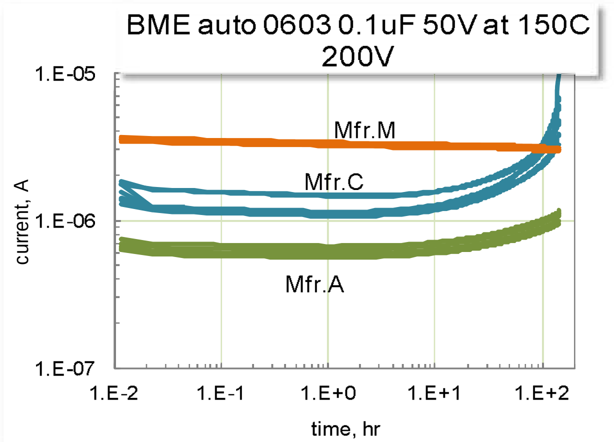
✓ Difference in HT DCL for PME and BME capacitors is mostly related to different height of the interface barriers. Also, typically d_{PME}>>d_{BME}.
Φ_B is 0.6 to 0.8 eV for BME and 1.1 to 1.3 eV for PMEs. The difference is due to concentration of V_O^{++}, rather than to work functions of Ni and Ag/Pd.

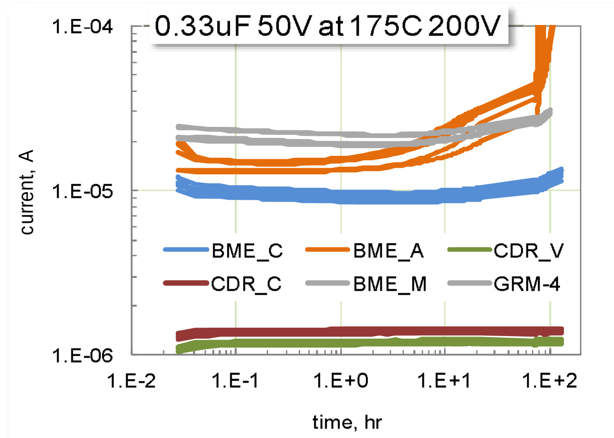
✓ At low *E*, *U(E)* dependence is stronger than predictions of the model. Possible reasons: $\Phi_{GB}(V)$, $\mu(E)$, and/or *P(E)* that stabilize at ~5 V/μm.

Leakage Currents at HALT

- Step stress HALT was carried out at T = 22°C, 125°C, 150°C, and 175°C, for 100 hours and 200V at each step.

Examples of variations of leakage currents with time during HALT



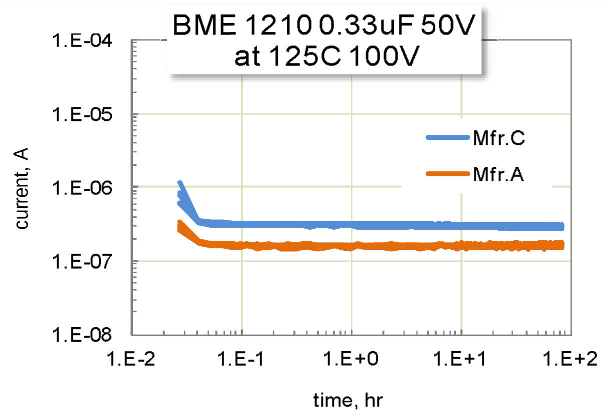


- ✓ Intrinsic degradation processes are similar for different samples from the same lot of capacitors.
- ✓ Different types of BMEs have different rates of degradation.
- ✓ Initial levels of currents do not correlate with the rate of degradation.

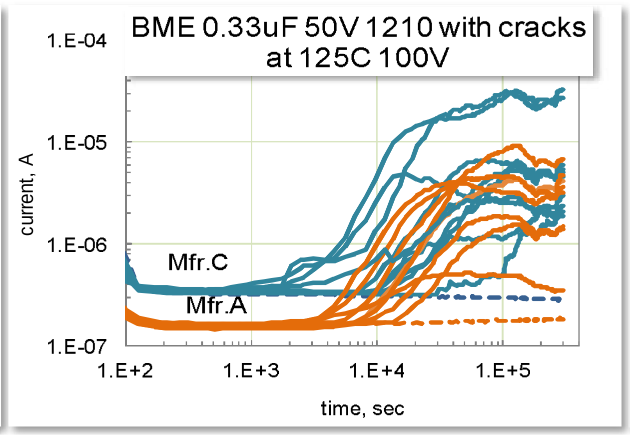
HALT of BME and PME capacitors with Cracks

Typical variations of currents through the testing

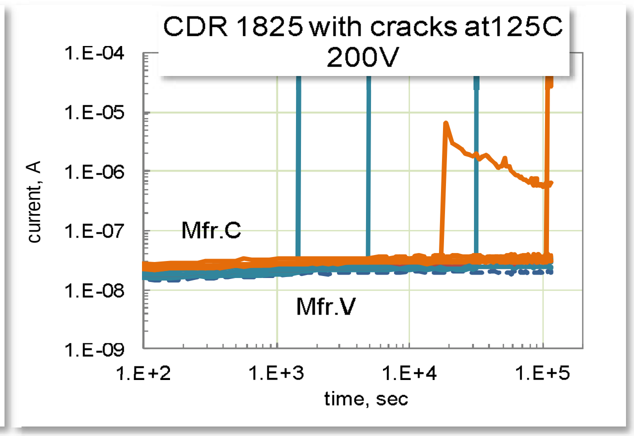
Virgin BME capacitors



BME MLCCs with cracks



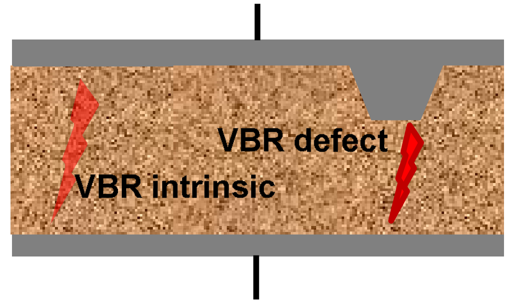
PME MLCCs with cracks

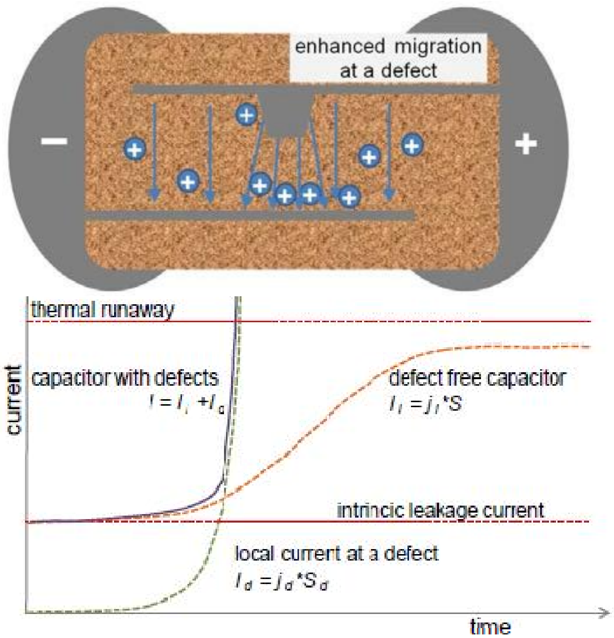


- ✓ Cracking does not affect IR that is measured at 125 °C but facilitates degradation of leakage currents in BMEs.
- ✓ In the presence of cracks currents start increasing after a few hours of testing, but stabilize with time.
- ✓ Degradation in PMEs with cracks occurs at much higher levels of stress, and contrary to BMEs results in instantaneous short circuit failures (due to HT silver migration?).

Defect-Related Degradation and Failures

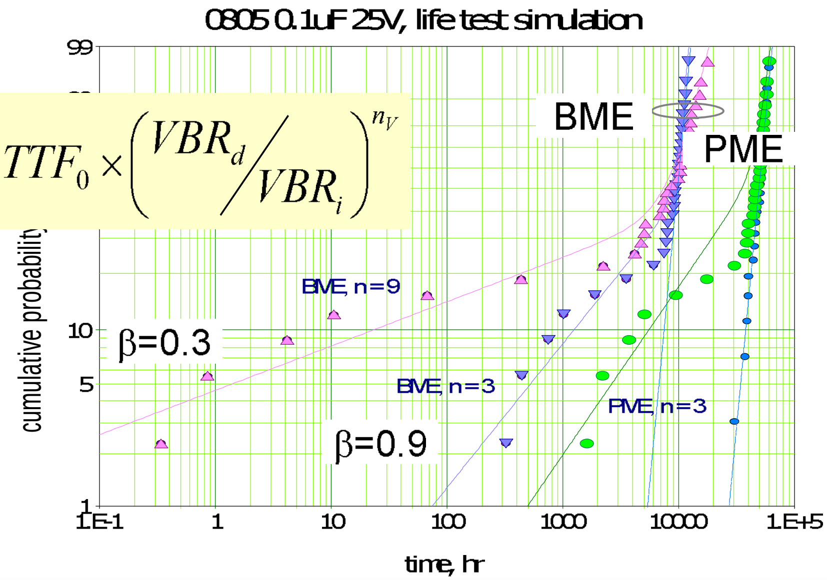
- The presence of a defect increases local electrical field and accelerates V_o^{++} migration.
- A ratio of defect-related and intrinsic breakdown voltages indicates the level of field increase.





TTFs calculated based on VBR distribution

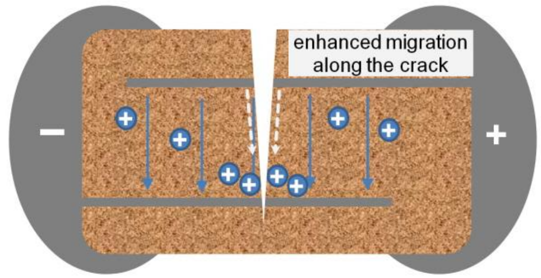
$$TTF = TTF_0 \times \left(\frac{VBR_d}{VBR_i} \right)^{n_V}$$



- ✓ IM failures occur when accumulation of V_o^{++} at a defect site is sufficient to increase current density to cause thermal runaway.
- ✓ Wear-out processes in the presence of defects result in IM failures.
- ✓ Small size defects might not cause thermal runaway and failures.

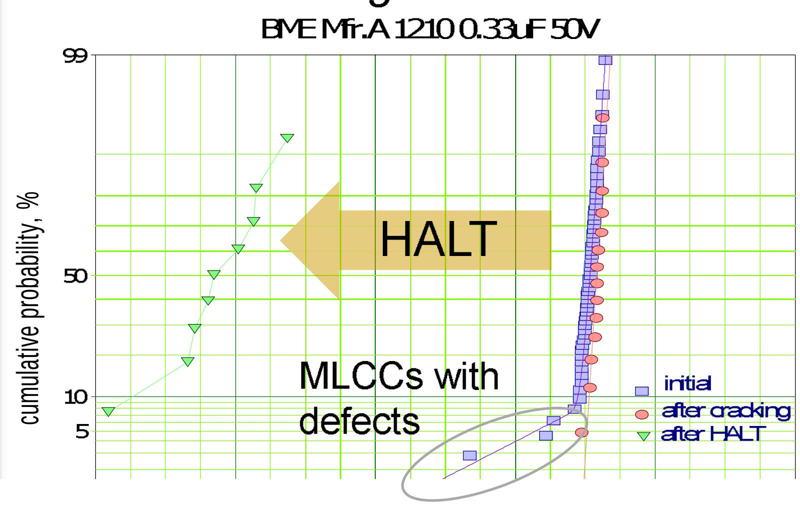
Effect of Cracks on Degradation of Leakage Currents and Failures

- Ionic diffusion/migration along the surface might be several orders of magnitude faster than in the bulk of ceramic.
- Migration along the surface of cracks facilitates local accumulation of V_o^{++} and accelerates degradation.
- An increase in local power dissipation reduces VBR.



- ✓ Due to V_o^{++} migration, defects, and cracks in particular, are more likely to cause failures in BMEs compared to PMEs.
- ✓ In the presence of moisture, the situation is reversed, and the probability of failures in BMEs is much less than for PMEs.

Effect of cracking and HALT on VBR



Conclusion

- At RT and V < 2VR, DCL is due to absorption processes and depends on capacitance and quasi static electric susceptibility. IR values at RT are typically 2 times greater for PMEs than for BMEs.
- Intrinsic leakage currents increase with voltage according to a power law with the exponent decreasing with temperature to ~1.5-2 at T ≥ 150 ºC. Activation energies of DCL decrease with voltage and at VR are ~1.2 eV for PMEs and ~0.8 eV for BMEs.
- Intrinsic conduction can be described using Simmons model at E > 5 V/μm. The difference in HT IR between military PMEs and commercial BMEs is mostly due to different barrier heights and thickness of the dielectric.
- Cracks might not affect IR at room and/or high temperatures, but accelerate degradation of DCL in BME capacitors.
- Currents in BME capacitors with defects might stabilize with time without causing catastrophic failures.
- A model of DCL degradation in MLCCs with defects is suggested.